# FYST17 Lecture 11
# BSM I

Thanks to G. Brooijmans, C. Grojean

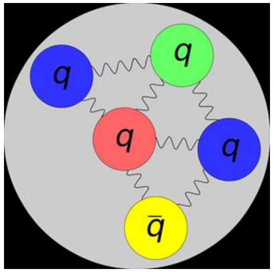
# Today & Monday

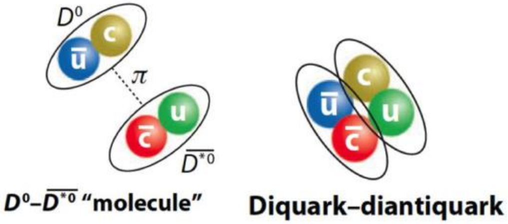
- Why go Beyond the SM?
  - What are the problems with the SM?
  - What direct measurements points to physics BSM
- Some attempts at solutions
  - Supersymmetry
  - Extended Higgs sector
  - Extra dimensions
  - A few others
- Searches for DM, gravitational waves

# Any direct evidence?

Certainly a few measurements that are not incorporated in the current Standard Model:

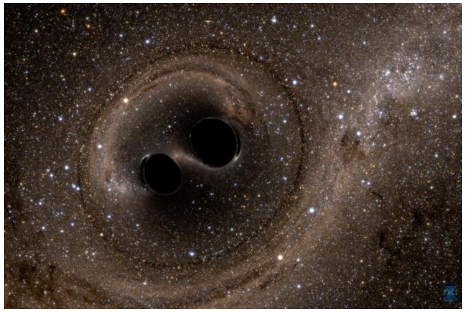
- Exotic baryons (X, pentaquarks etc)



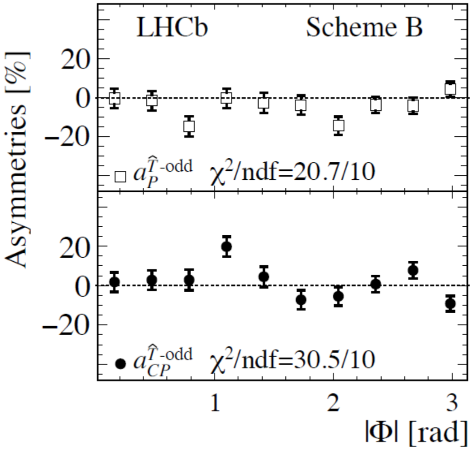




- Neutrino masses!

- (Gravitational waves)



- The new LHCb CP violation measurement (although <4σ)



# Status of the Standard Model

19 parameters ( + $\nu$ masses)

Tested to precision level $10^{-3} - 10^{-12}$

} Extremely successful!

But empirically incomplete

Structure quite complicated

Aesthetically unacceptable

Many problems with naturalness

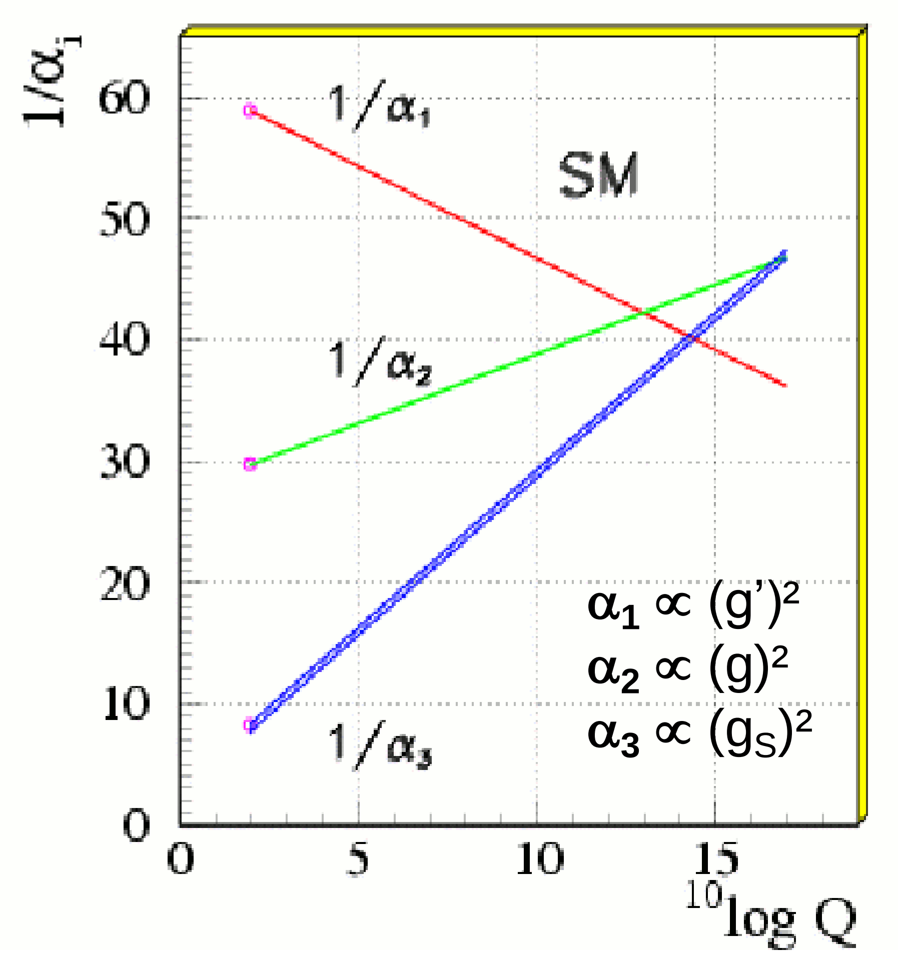
No quantum gravity

Missing answers to ”big” questions

# Examples of answers we need

- *What is the origin of CP violation?*
- *What is the origin of the matter/anti-matter asymmetry*
- *Why three gauge forces (so far)? And three generations?*
- *Why is the strong interaction strong? Why only left-handed particles participate in weak force?*
- *Gravity? Is there a unified description of all forces?*
- *Why is mass(W/Z/H) << mass(Planck)? (Hierarchy problem)*
- *Why is charge quantized?*
- *What is Dark Matter and Dark Energy? (and why Dark Energy now?)*
- *What was the Big Bang?*

# Unification of coupling constants?

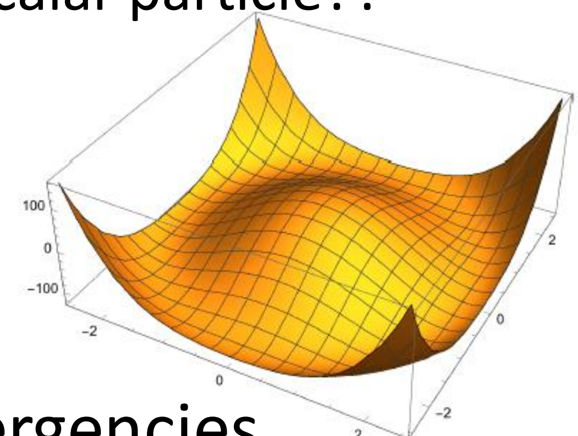



Extrapolating the Standard Model coupling constants to higher energies

http://pdg.lbl.gov

# The Higgs discovery just adds to that list...

- What is it, really, a condensate in our Universe?
- Is it elementary?
  - If yes, why is there only 1 fundamental scalar particle??
- Why does it have mass$^2$ $\mu^2 < 0$ ?!




- Higgs mechanism gives quadratic divergencies
  - (see later)

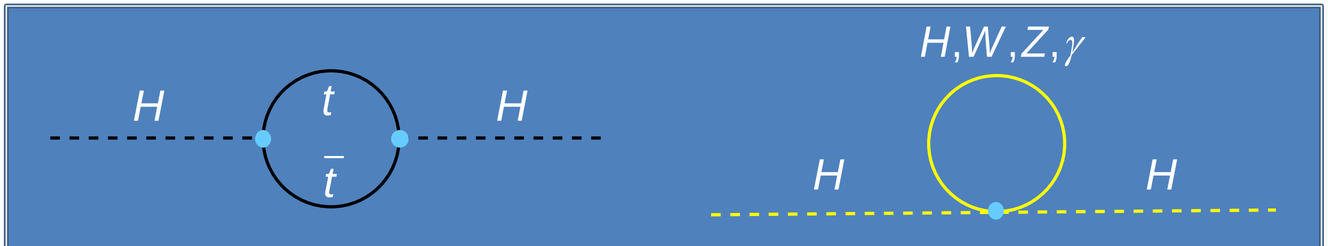
# Is the Standard Model really fundamental?

- Does not appear so ( $\gtrsim$ 25 parameters?!)
- Evidence of selective processes:
  - For instance, no neutral colored fermions
  - $q_d = q_e$ /N(colors) $\Rightarrow$ grand unification?
- ***Fragile:*** small changes in parameters $\Rightarrow$ very different physics!
  - If $m_d < m_u$: all protons decay $\Rightarrow$ no atoms
  - If $m_e > 4m_p - m_\alpha$ $\Rightarrow$ Sun doesn't burn $\Rightarrow$ no us
  - If v >> TeV $\Rightarrow$ $|m_n - m_p|$ large , rapid neutron decay $\Rightarrow$ no chemistry nor life

# The "Gauge Hierarchy Problem"

**Discover of Higgs boson with mass < 1 TeV means the Standard Model is complete !**

However, when computing radiative corrections to the bare Higgs mass a problem occurs:




Higgs radiative corrections

$$m_H^2 = m_0^2 + \delta m_H^2 \quad \text{where:} \quad \delta m_H^2 \propto \int_0^\infty d^4k \frac{k^2 + m_f^2}{\left(k^2 + m_f^2\right)^2} + \ldots \xrightarrow{\text{cut-off}} \int_0^{\Lambda_{\text{cut-off}}} (\ldots) \propto \Lambda_{\text{cut-off}}^2$$

Integral quadratically divergent

The cut-off sets the scale where new particles and physical laws must come in

Above the EW scale we only know of two scales: GUT (~$10^{16}$ GeV) and Planck (~$10^{19}$ GeV)

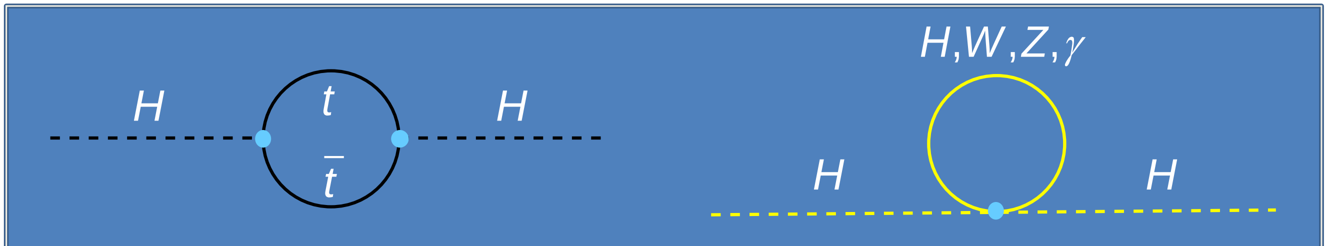
Such a cut-off would require an incredible amount of finetuning to keep $m_H$ light

$$m_H^2 = (125\ GeV)^2 = m_0^2 + C \cdot \Lambda_{cut-off}^2$$

# The “Gauge Hierarchy Problem”

**Discover of Higgs boson with mass < 1 TeV means the Standard Model is complete !**

However, when computing radiative corrections to the bare Higgs mass a problem occurs:




Higgs radiative corrections

$$m_H^2 = m_0^2 + \delta m_H^2 \quad \text{where:} \quad \delta m_H^2 \propto \int_0^\infty d^4k \, \frac{k^2 + m_f^2}{\left(k^2 + m_f^2\right)^2} + \ldots \xrightarrow{\text{cut-off}} \int_0^{\Lambda_{\text{cut-off}}} (\ldots) \propto \Lambda^2_{\text{cut-off}}$$

Integral quadratically divergent

Missing protection of scalar Higgs mass is related to **absence of a symmetry principle**. Setting $m_H = 0$ in SM Lagrangian, **does not restore any symmetry in the model**.

New physics models should address this. $M_H$ should become a deviation from some exact symmetry, and is thus **intrinsically small** !

$$m_H^2 = (125\ GeV)^2 = m_0^2 + C \cdot \Lambda^2_{cut-off}$$

# Hunting for Answers

- Get more information
  - Measure particles and their interactions in detail
    - Precision measurements (e.g. LHCb)
  - Observe new particles or interactions
    - Search in new areas in "phase space"
- Find the underlying pattern(s)
  - Hypothesize, build models
    - Internally consistent? Consistent with data?
    - Suggestions on where to look

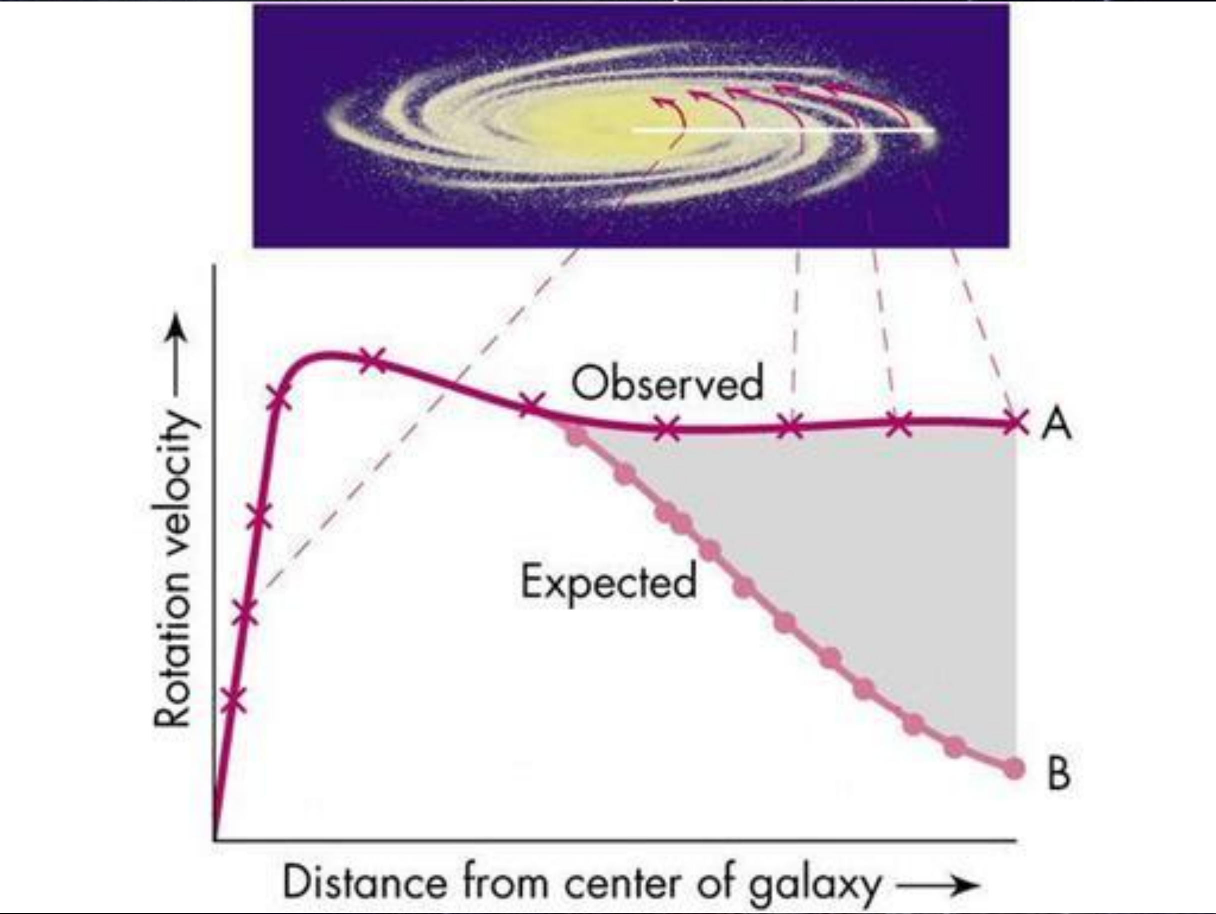
Experiment

Theory

# Where to Start?

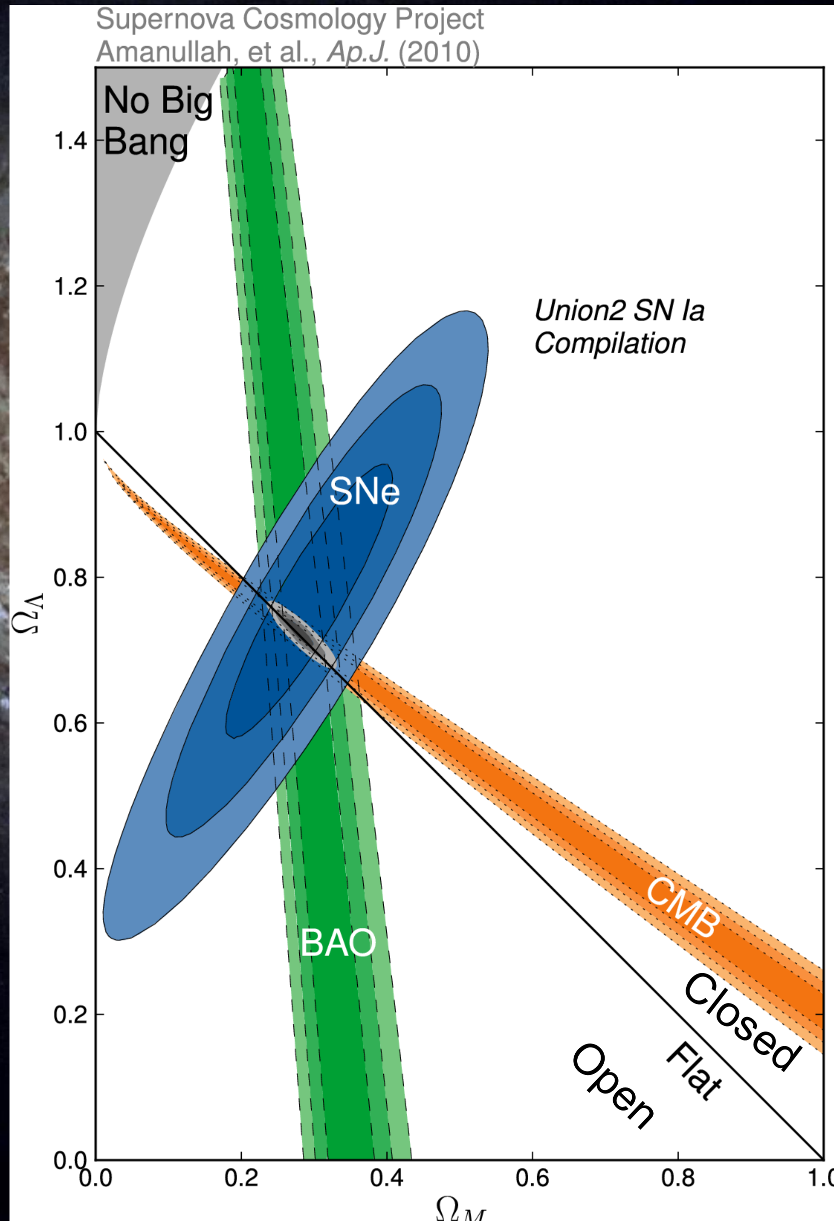
- BSM physics **must** couple to SM (weakly?), but is it
  - Resonant?
    - Does it have new massive particles decaying to electrons, muons, quarks, W, Z,…?
  - "SM-like"?
    - Same but includes some new long-lived particles in the decay chain... (e.g. dark matter candidate)
  - No new "particles" in reach
    - Hidden or too heavy or.... don't exist
  - Are there new interactions?

# Galaxy rotation curves




**Standard Model only accounts for ~20% of the matter of the Universe!!!**

# Supernovae data

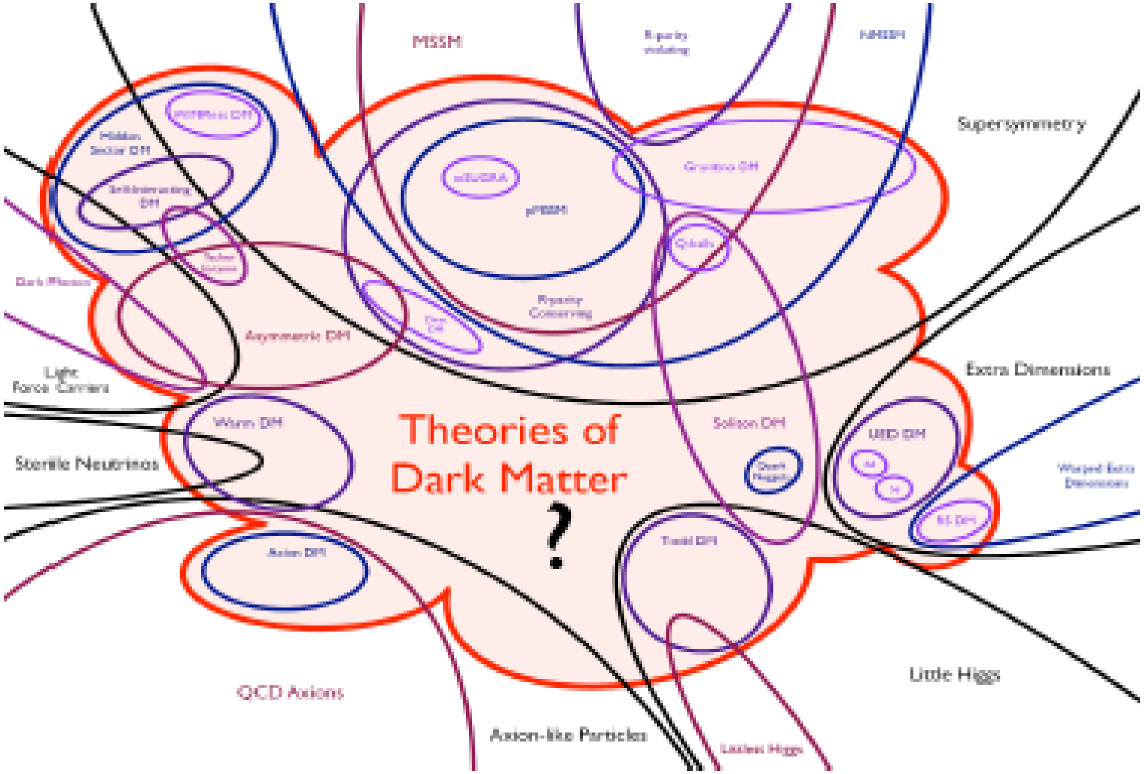



"Cosmological constant" term

"Matter density" term

Matter only accounts for ~30% of the Universe!

# The energy scale(s) of new physics




T. Tait, DM@LHC '14

The prediction about the mass scale of DM comes with large error bars:

$$10^{-22}\,\mathrm{eV} < m_{DM} < 10^{20}\,\mathrm{GeV}$$

(ALPs) (Wimpzillas, Q-balls)

# Supersymmetry (SUSY)

# Idea

New symmetry ***fermions*** $\leftrightarrow$ ***bosons***

This symmetry is the most general extension of Lorentz invariance

SUSY has: $N_{dof}$ (bosons) = $N_{dof}$ (fermions)
[cf. SM: $N_{dof}$ (bosons) << $N_{dof}$ (fermions)]

| Spin 0 | Spin 1/2 | Spin 1 | Spin 3/2 | Spin 2 |
|---|---|---|---|---|
| sLeptons | Leptons | | Gravitino | Graviton |
| sQuarks | Quarks | | | |
| Higgs | Higgsino | | | |
| | Photino | Photon | | |
| | Zino | Z | | |
| | Wino | W | | |
| | Gluino | Gluon | | |

- To create *supermultiplets*, we need to add one *superpartner* to each SM particle
- Superpartners have opposite spin statistics but otherwise equal quantum numbers
- Need to introduce an additional Higgs doublet to the non-SUSY side $\rightarrow$ 5 Higgs bosons

But where are these partners?!
Supersymmetry must be broken (if realized)

# Particle spectrum (minimal!)

In reality the new states would mix

Several ideas of how the supersymmetry is broken – intimately connected with EWK symmetry breaking

SM

SUSY

Eigenstates of mass

| Spin 0 | Spin 1/2 | Spin 1 |
|---|---|---|
| $\tilde{\ell}_1, \tilde{\ell}_2$ | $\ell$ | |
| $\tilde{q}_1, \tilde{q}_2$ | $q$ | |
| $h^0, H^0, A^0, H^\pm$ | $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ | |
| | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$ | $\gamma, Z^0, W^\pm$ |
| | $\tilde{g}_a$ | $g_a$ |

Squark/slepton mixing proportional to SM partner masses

→ largest for 3rd gen.

→ can become lightest squarks / sleptons

The gauge-mixed physical states that propagate in space and time and that can be observed.

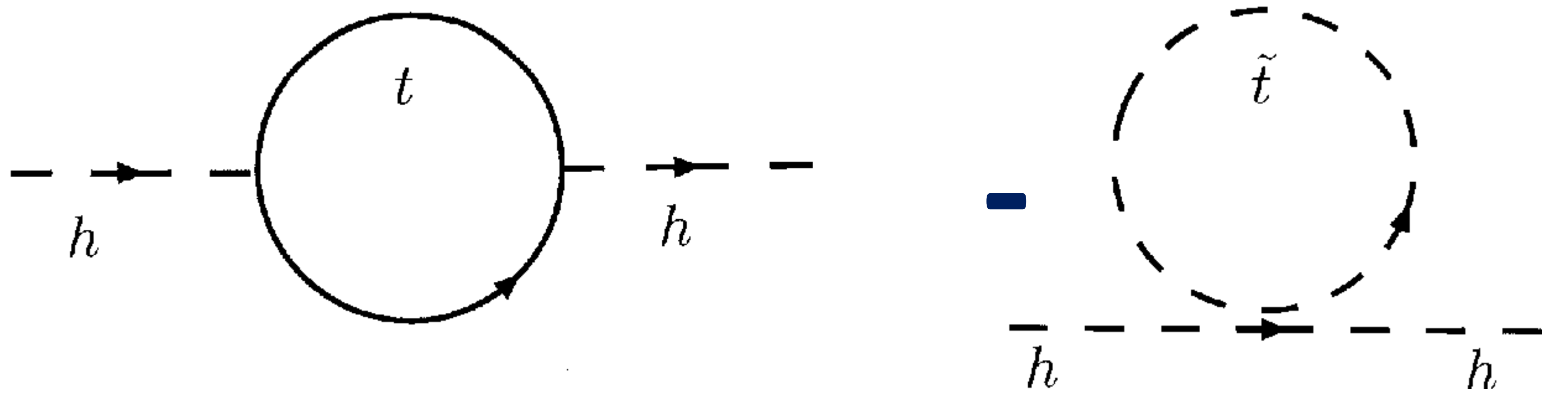
Neutralinos: mass eigenstates of photinos, zinos, neutral higgsinos

Charginos : mass eigenstates of winos and charged higgsinos

Since we don't know the mechanism, have to introduce $\mathcal{O}(100)$ new parameters

# SUSY and the hierachy problem

If Supersymmetry not broken we would have perfect cancellation in the loops!



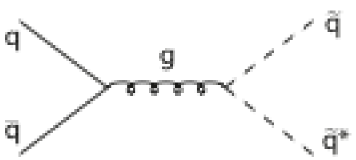

But as m($\tilde{t}$) $\neq$ m($t$) they do not quite cancel, instead just a suppression

This still gives a decent result if |m(fermion) – m(boson)| < $\mathcal{O}$(TeV)

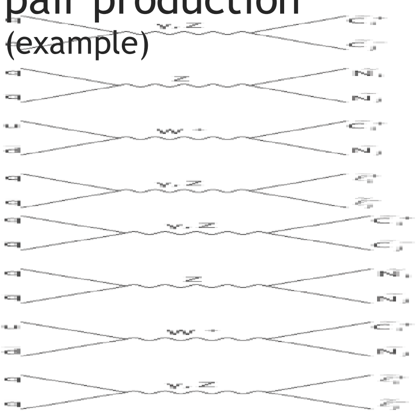
# Once mass spectrum fixed, all cross sections predicted

Spin structure of SUSY spectrum: lower $\sigma$ than other BSM models, harder to find !

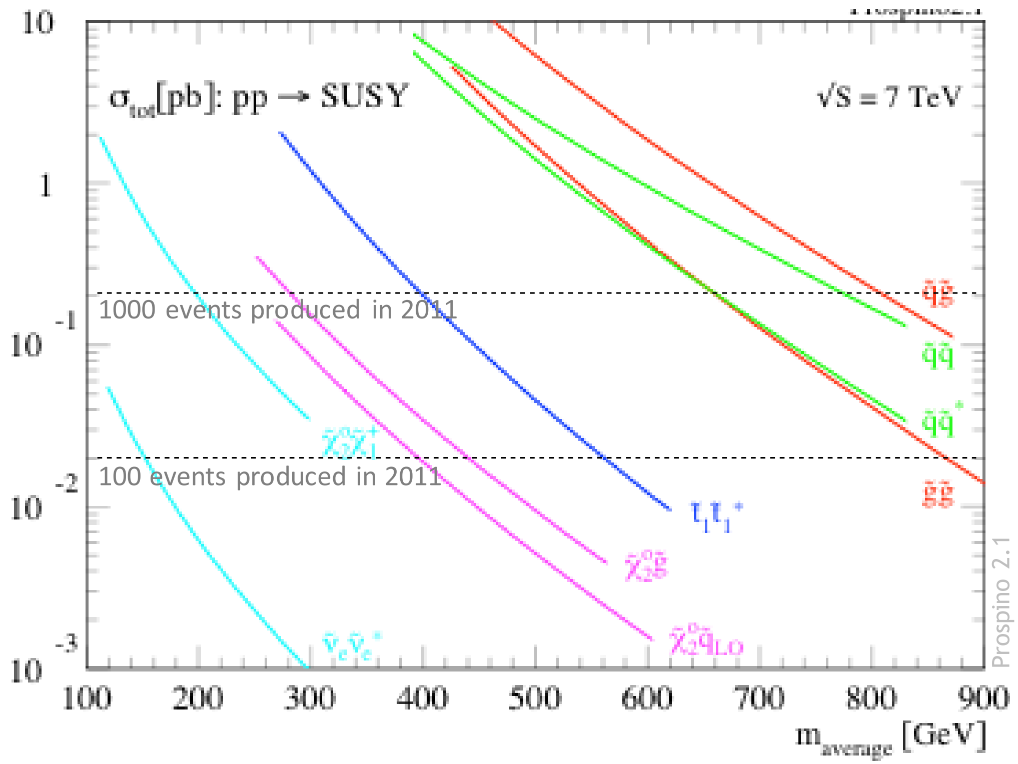
Direct squark pair production (example)



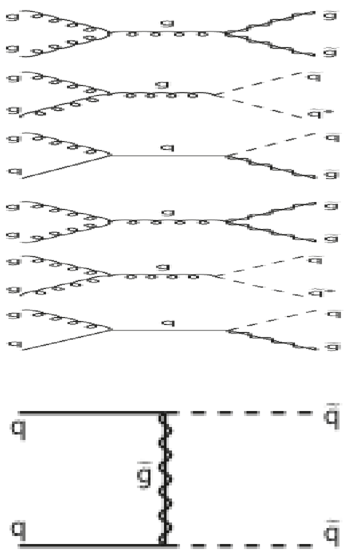
Direct gaugino/slepton pair production (example)



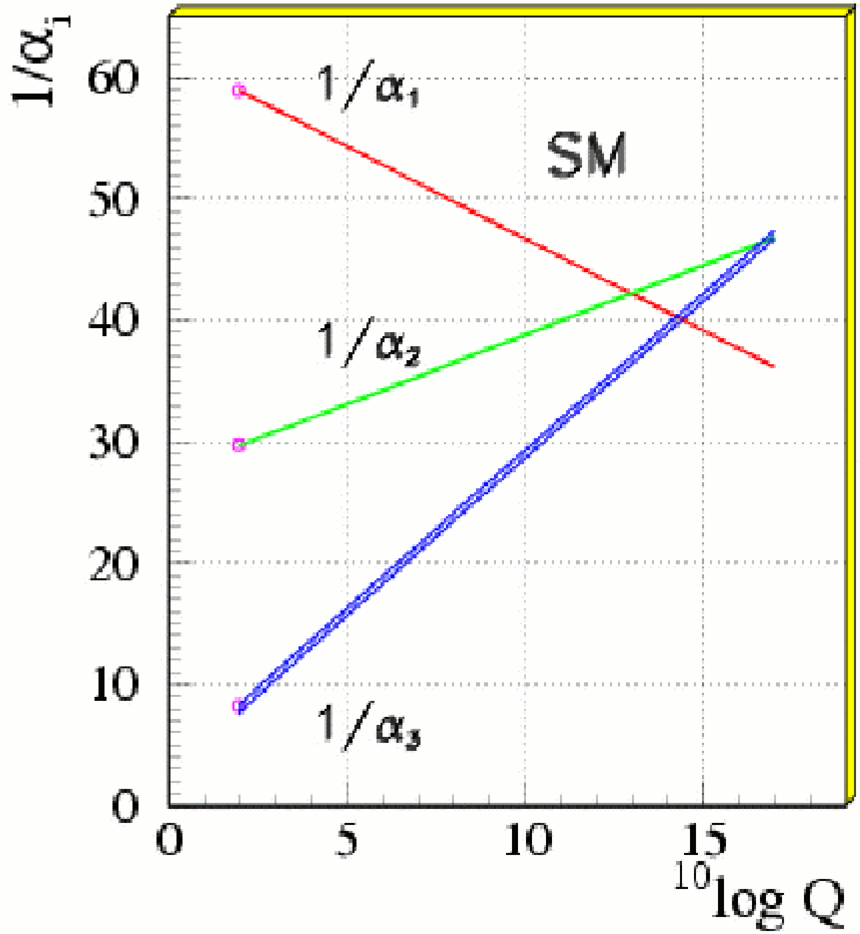
SUSY cross section versus sparticle mass

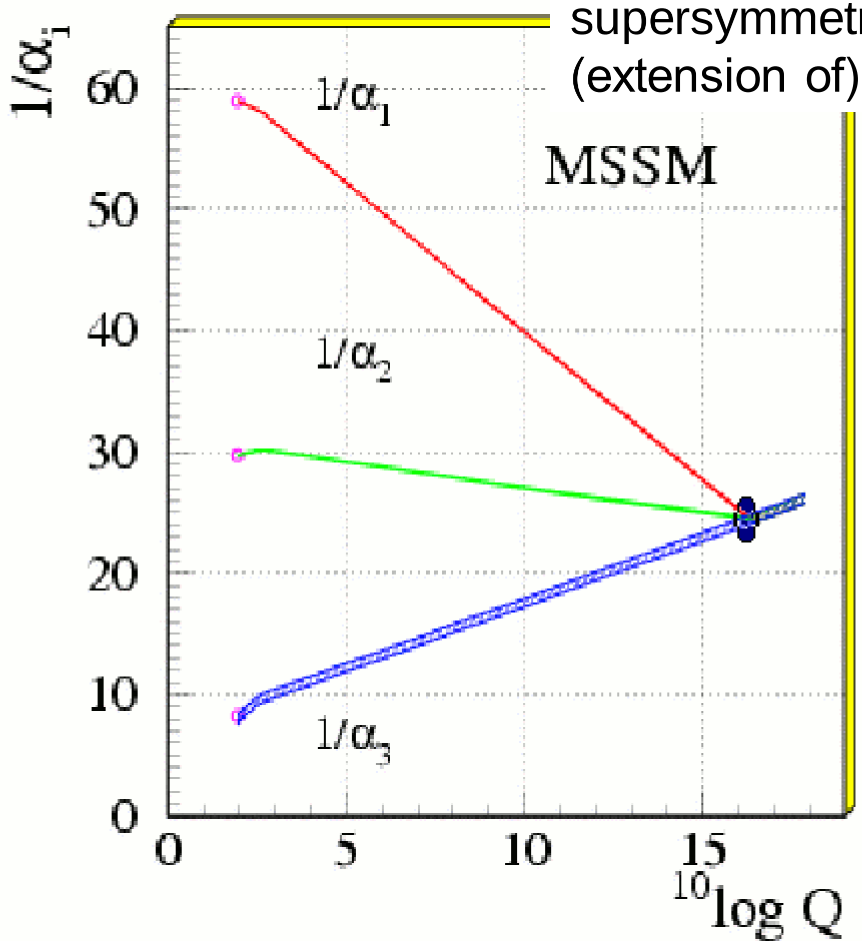



Gluino & squark production (examples)



# Unification of coupling constants with supersymmetry



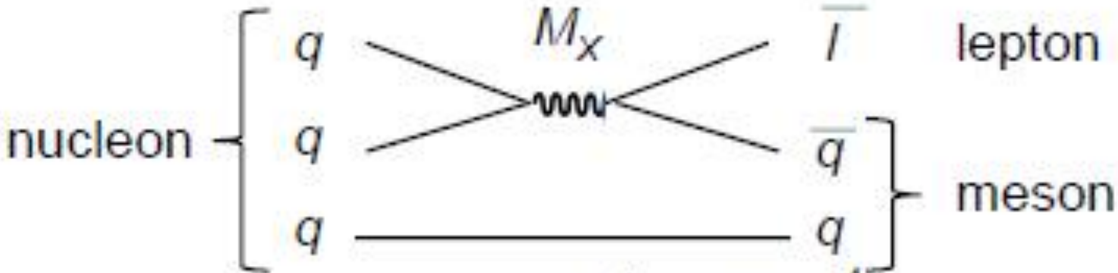

"minimal supersymmetric (extension of) SM"

# Proton Decay

(G. Giudice SSLP'15)

in GUT, matter is unstable

decay of proton mediated by new SU(5)/SO(10) gauge bosons

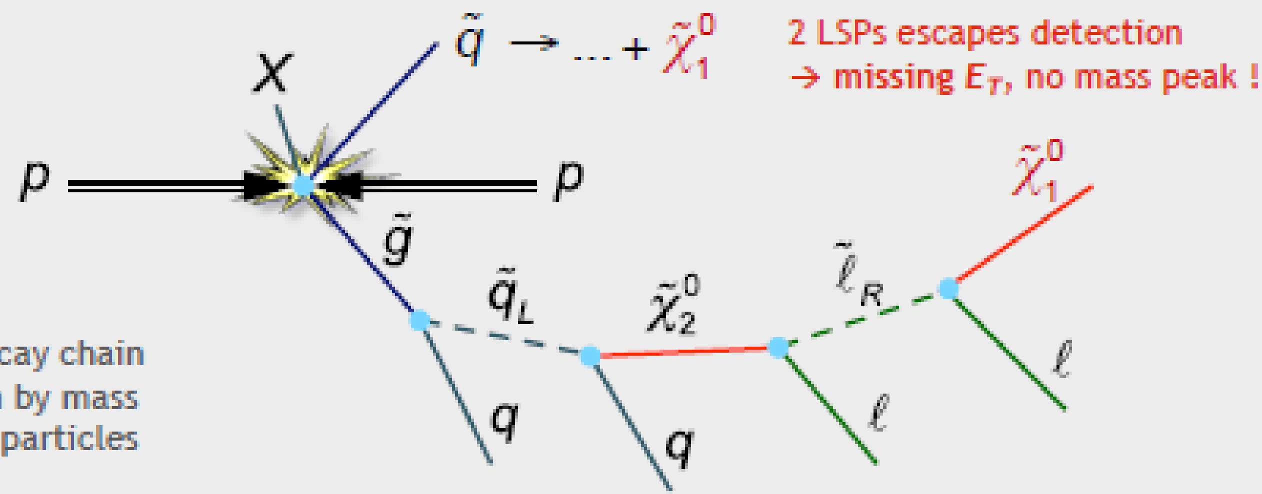



$$\text{GUT:}\quad \tau_p(p \to e^+\pi^0) = \left(\frac{M_X}{10^{15}\ \text{GeV}}\right)^4 10^{31\text{–}32}\ \text{yr}$$

$$\text{Exp:}\quad \tau_p(p \to e^+\pi^0) > 8.2 \times 10^{33}\ \text{yr}$$

# Characteristic SUSY Decay Cascades

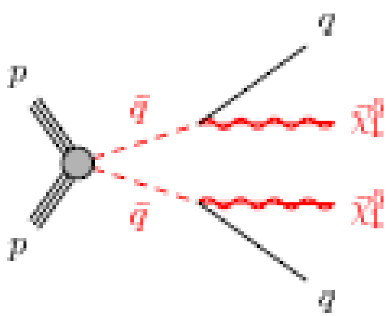
- To avoid proton decay, a new conserved quantum number ($R$) is introduced, which forces a SUSY particle to decay in at least one other SUSY particle
- The lightest SUSY particle is thus stable (LSP), and must be neutral and colourless → WIMP (dark matter candidate)
- Typical **LSP is spin-½ neutralino.** It could also be a gravitino
- With $R$ parity: SUSY production in pairs only → requires energy 2 × SUSY mass !

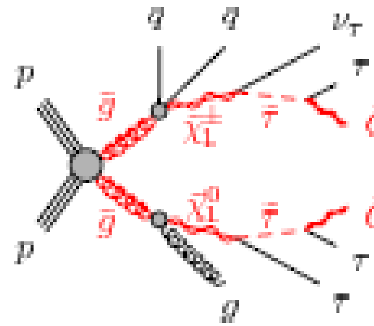


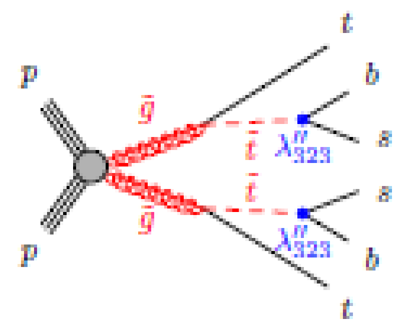

"Typical" SUSY decay chain at the LHC, driven by mass hierarchy of SUSY particles

# Canonical SUSY

- Wide range of signatures
  - Strong production… (large cross-section)

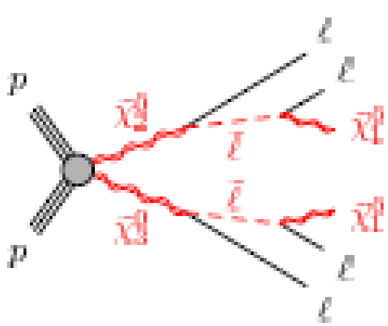


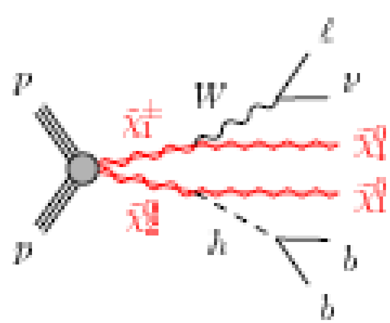


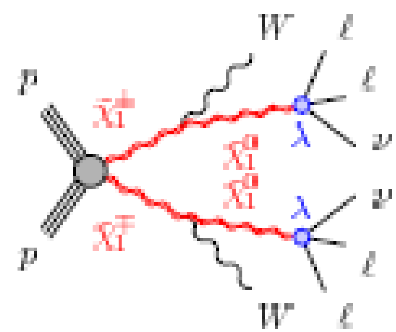


  - … or weak production

RPV



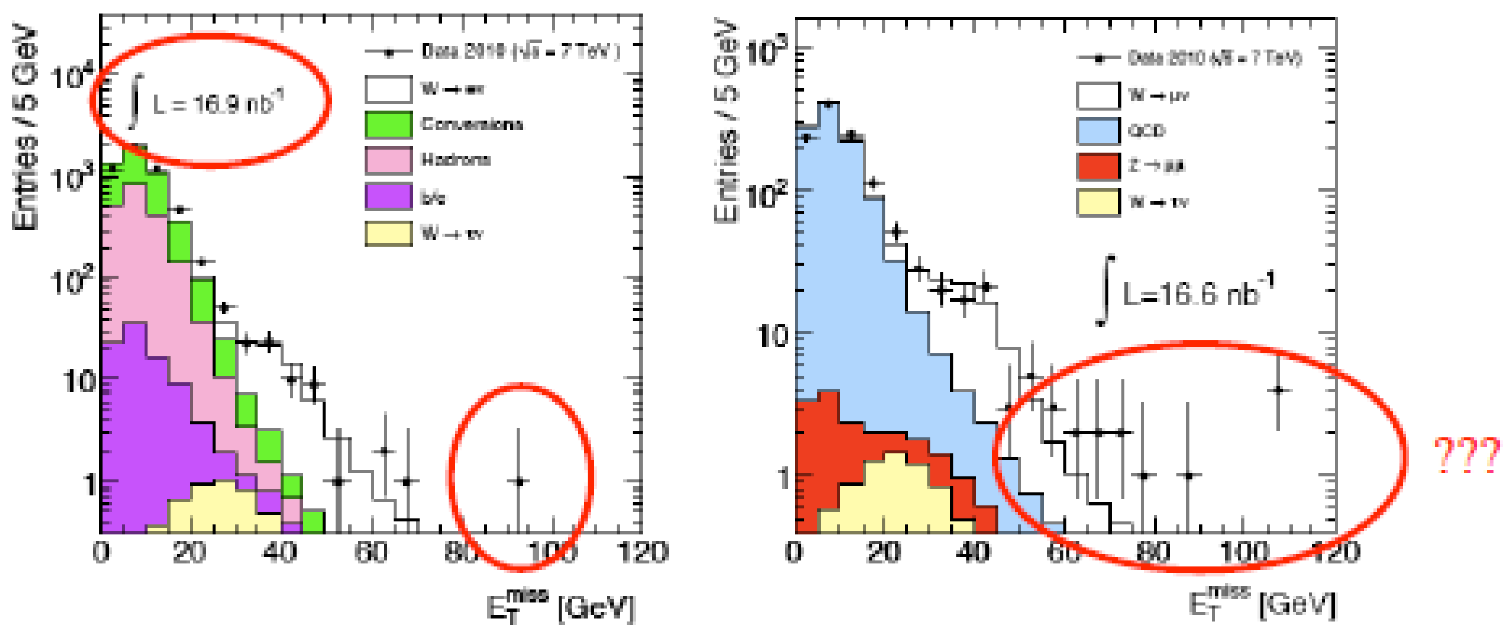




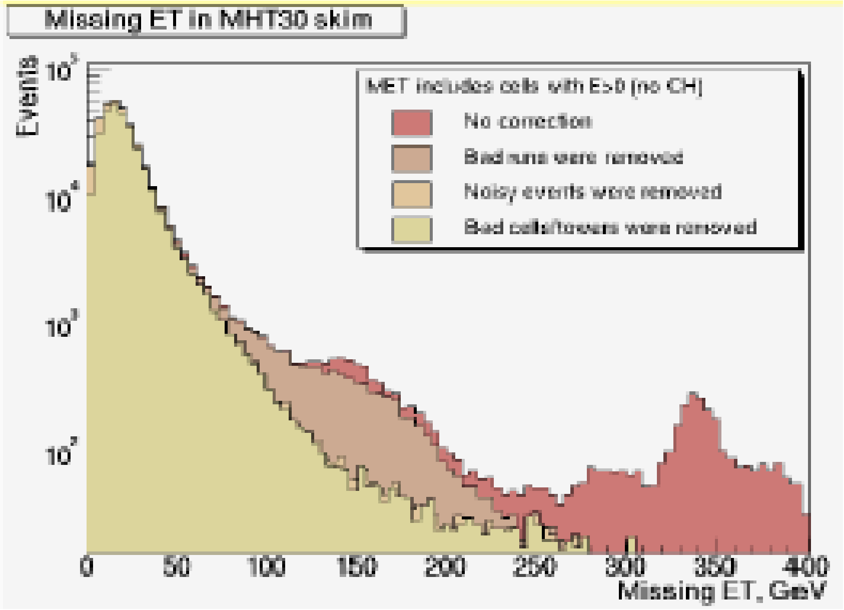
# Missing ET

- "Evil" variable: - Σ (everything else)
  - Need to understand "everything else"
  - Good benchmark: leptonic W boson decays

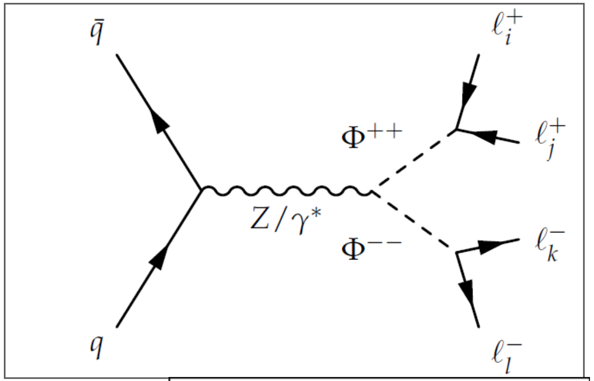
Early 2010

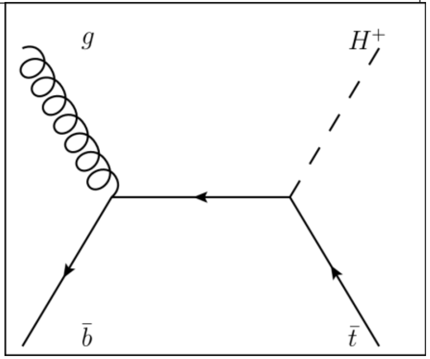


- Analyses using MET are particularly sensitive
  - Requires the full calorimeter to behave, and calorimeter is generally the most sensitive subdetector (analog, ~16 bits)
  - Easy: basic DQ (high voltage trip, etc.)
  - Hard: low frequency
  - Can't spot a $10^{-5}$ Hz (once a day) effect online or in first pass DQ
    - But can be biggest part of dataset after cuts!



# Extended Higgs sector




In the Standard Model single Higgs doublet, often

written as $\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$ or $\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$

**Extended:** Many choices but a few constraints,

for instance suppression of FCNC and $\frac{M_W}{M_Z} = \cos\theta_W$

- Most successful: 2 Higgs doublet models (2HDMs)
  - Supersymmetry uses this
- See-saw models predict Higgs triplet with $\varphi^0$, $\varphi^{+/-}, \varphi^{++/--}$

# General 2HDM Potential

$$V(\phi_1,\phi_2)=\lambda_1\left(|\phi_1|^2-v_1^2\right)^2+\lambda_2\left(|\phi_2|^2-v_2^2\right)^2$$
$$+\lambda_3\left[\left(|\phi_1|^2-v_1^2\right)+\left(|\phi_2|^2-v_2^2\right)\right]^2$$
$$+\lambda_4\left[|\phi_1|^2|\phi_2|^2-\left(\phi_1^{*T}\phi_2\right)\left(\phi_2^{*T}\phi_1\right)\right]$$
$$+\lambda_5\left[\mathrm{Re}\left(\phi_1^{*T}\phi_2\right)-v_1v_2\cos\xi\right]^2$$
$$+\lambda_6\left[\mathrm{Im}\left(\phi_1^{*T}\phi_2\right)-v_1v_2\sin\xi\right]^2$$

All $\lambda$ are real.

From "Higgs Hunter's guide".

$$\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}_1=\begin{pmatrix}0\\ v_1\end{pmatrix}\frac{1}{\sqrt{2}}\quad;\quad\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}_2=\begin{pmatrix}0\\ v_2e^{i\xi}\end{pmatrix}\frac{1}{\sqrt{2}}\quad;\quad\tan\beta=\frac{v_2}{v_1}$$

# Higgs Boson Spectroscopy

- One Charged Higgs with mass:

$$m_{H^\pm} = \sqrt{\lambda_4 (v_1^2 + v_2^2)}$$

- One CP-odd neutral Higgs with mass:

$$m_{A^0} = \sqrt{\lambda_6 (v_1^2 + v_2^2)}$$

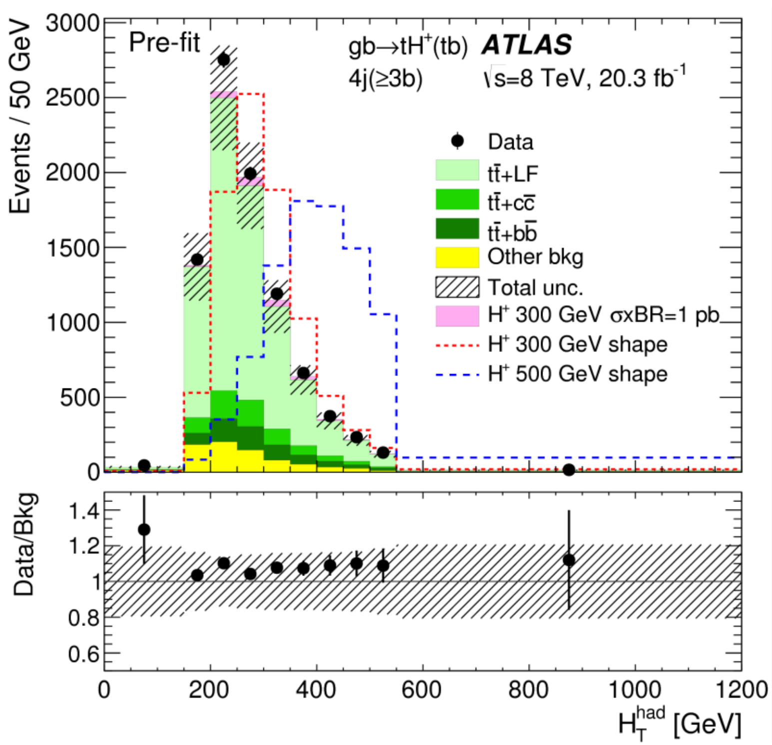
- And two CP-even higgs that mix.

$$M = \begin{pmatrix} 4v_1^2(\lambda_1 + \lambda_3) + v_2^2\lambda_5 & (4\lambda_3 + \lambda_5)v_1 v_2 \\ (4\lambda_3 + \lambda_5)v_1 v_2 & 4v_2^2(\lambda_2 + \lambda_3) + v_1^2\lambda_5 \end{pmatrix}$$

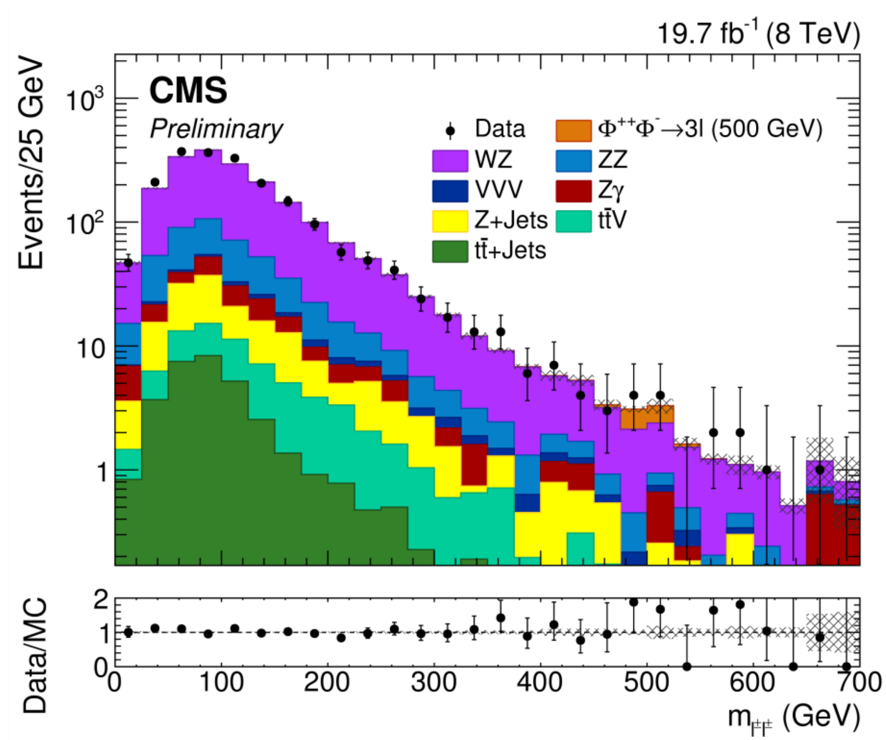
5 Higgs bosons! h, H, A, $H^\pm$

# Examples of searches for extra Higgs bosons

Singly-charged




Doubly-charged




Limits around $\mathcal{O}$(200 GeV ) 600 GeV

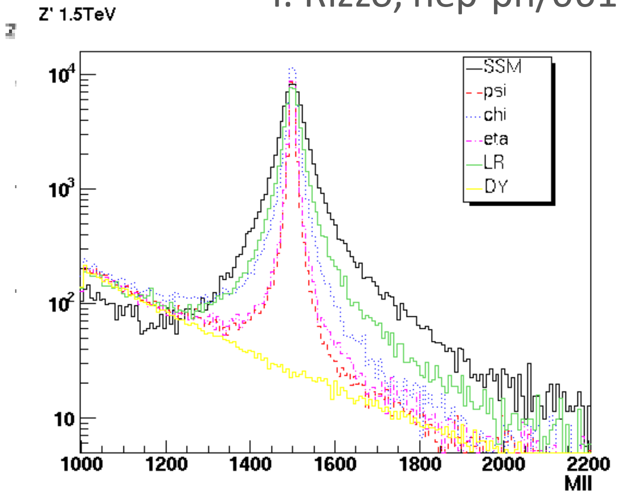
# Parity Restoration: Signals

- Primary signals are (right-handed) W' (+ Z')
  - Dilepton resonances (Z') offer clean signals, well-understood backgrounds
    - At LHC, some concern about extrapolation of calibration from Z to very high energies
    - Electron/muon resolution improves/degrades with $p_T$
  - $t\bar{t}$ decays visible
  - $\nu_R$ is presumably heavy, W' may not decay to leptons
    - Only dijet or diboson
    - If $\nu_R$ lighter than W'/Z', $\nu_R$ decays become important
- Note: many kinds of Z' - review by Langacker arXiv:0801.1345
  - W'/Z' would also require new fermions…

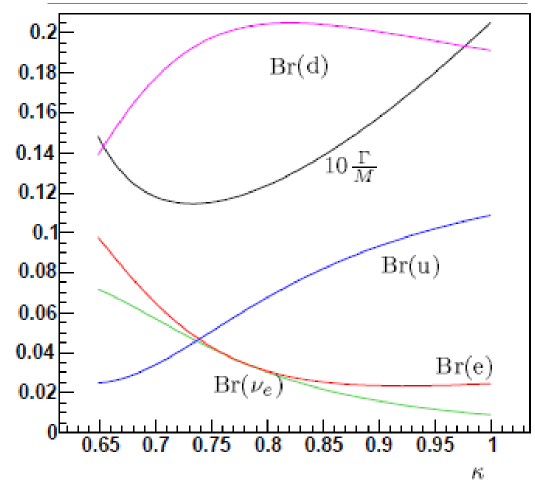
# Z' Production and Decay

T. Rizzo, hep-ph/0610104

- Production from u, d quarks is dominant at LHC
  - Couplings vary by model
  - E.g. for LR symmetric models, $\kappa = g_R/g_L$ drives production cross-section (convolute with PDFs) and branching ratios
- Decays somewhat similar to Z (but almost no BR to light neutrinos, decays to top open up), plot assumes $\nu_R$ heavier

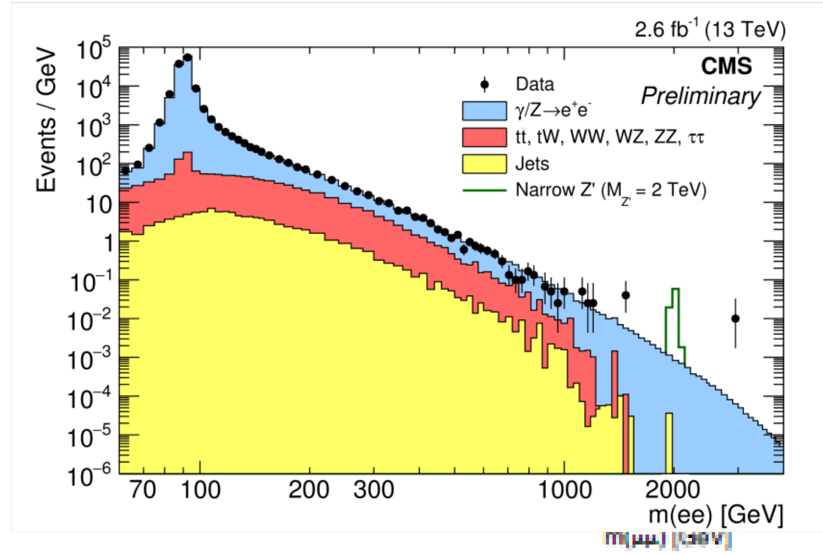


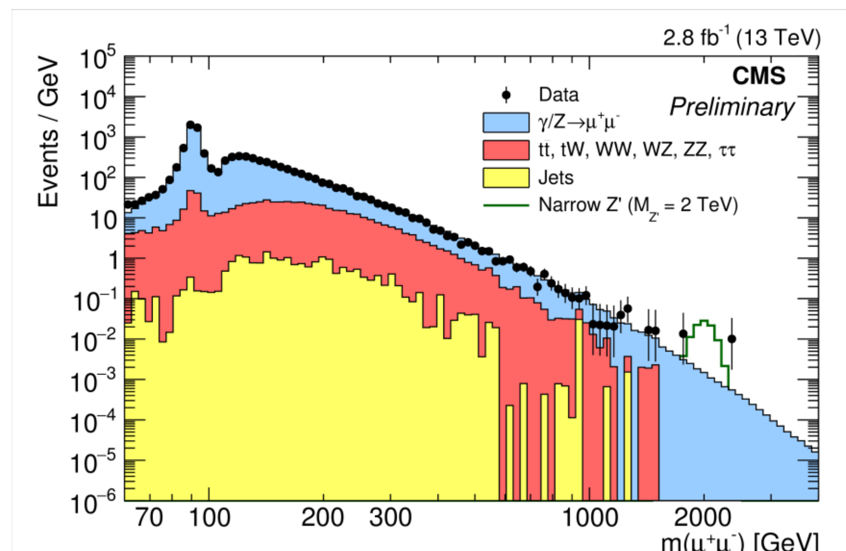

ATL-PHYS-PUB-2005-010



# Z’ → ee/μμ

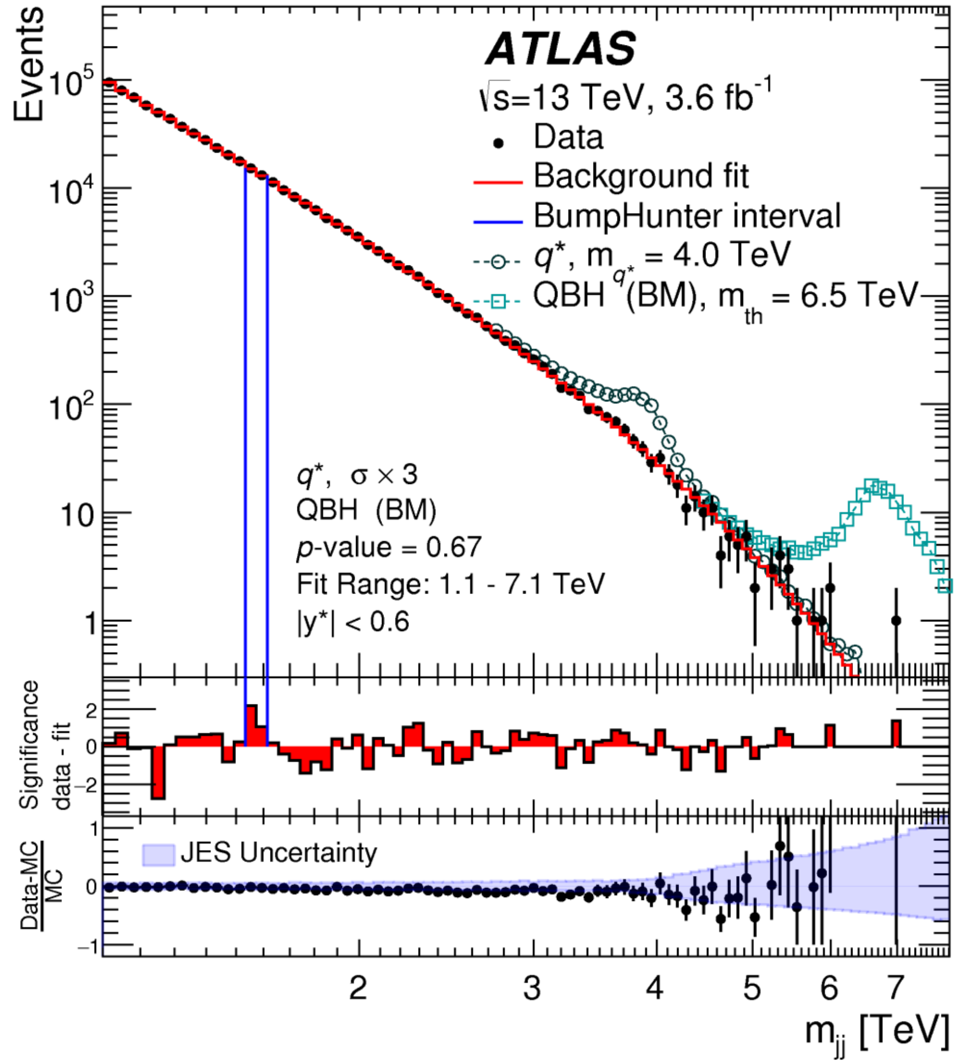
- ❖ Most promising channels:
  - Backgrounds very low!
  - “Self-calibrating”
  - In ee, at high masses, energy resolution dominated by constant term
    - 10 GeV for 1.5 TeV electron
    - Could measure width!
- ❖ LHC extended Tevatron reach immediately!



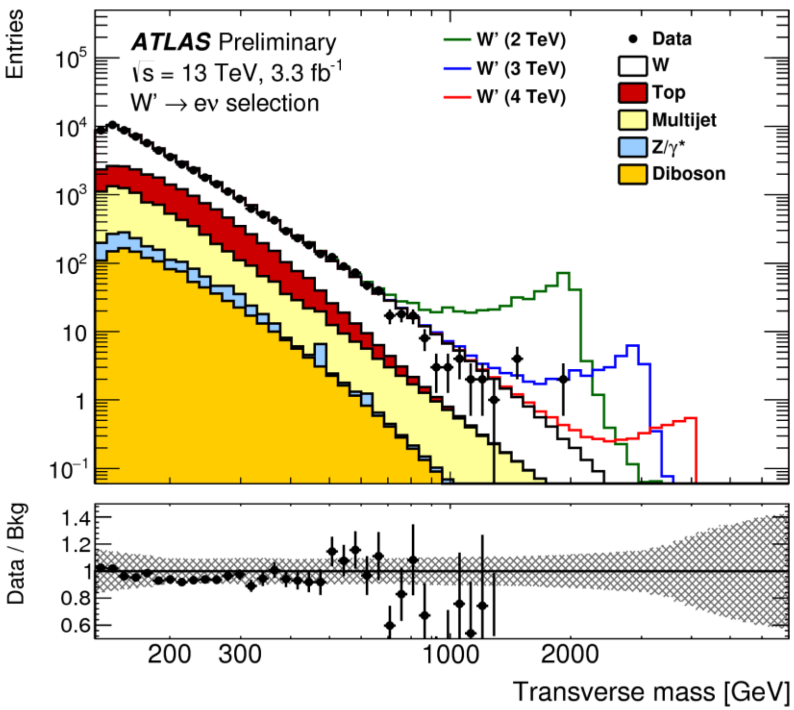
# Dijets

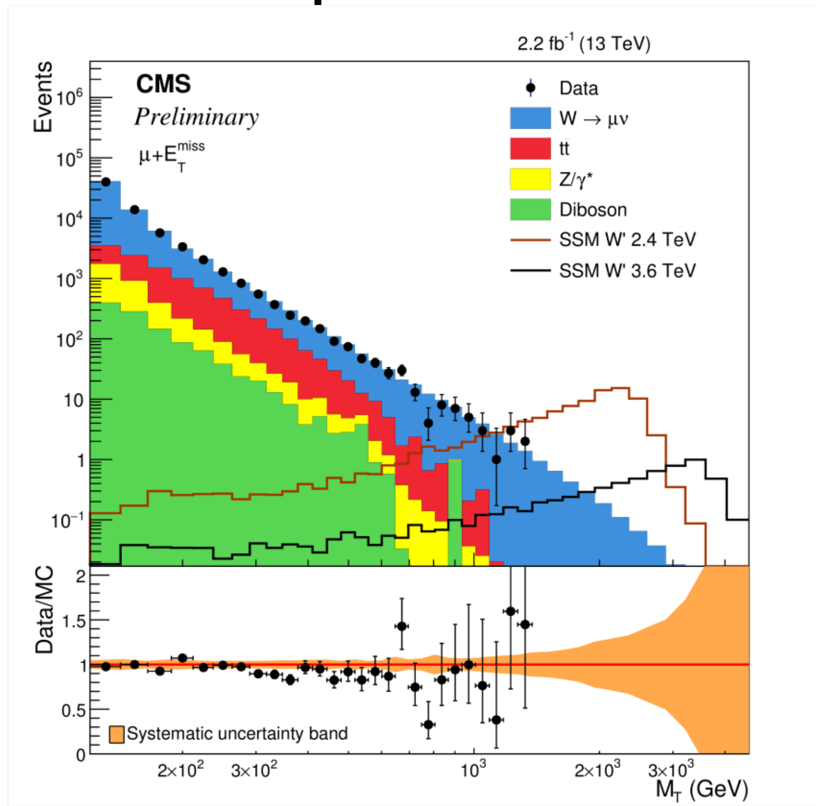
- SM background obviously much larger
  - But single source
  - And opens the door to strongly interacting objects



# W’ → μν / eν

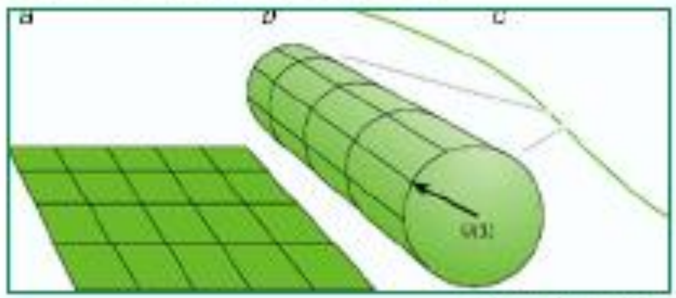
Another very simple selection: lepton + MET



# Extra Dimensions

- A promising approach to quantum gravity consists in adding extra space dimensions: string theory
  - Additional space dimensions are hidden, presumably because they are compactified



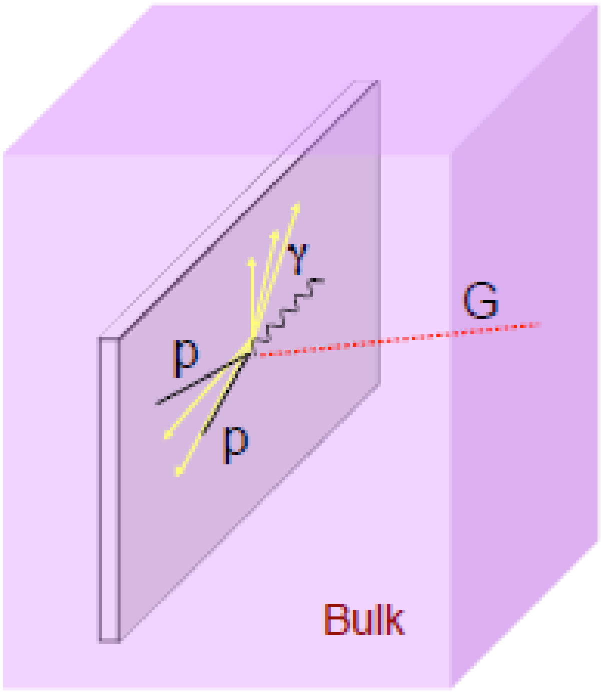
Source: PhysicsWorld

- Radius of compactification usually assumed to be at the scale of gravity, i.e. $10^{18}$ GeV
  - In '90 Antoniadis realized they may be much larger...

Phys.Lett.B246:377-384,1990

# ADD extra dimensions

- "Large extra dimension" scenario (developed by Arkani-Hamed, Dimopoulos and Dvali): Phys.Lett. B429 (1998) 263-272
  - Standard model fields are confined to a 3+1 dimensional subspace ("brane")
  - Gravity propagates in all dimensions
  - Gravity appears weak on the brane because only felt when graviton "goes through"

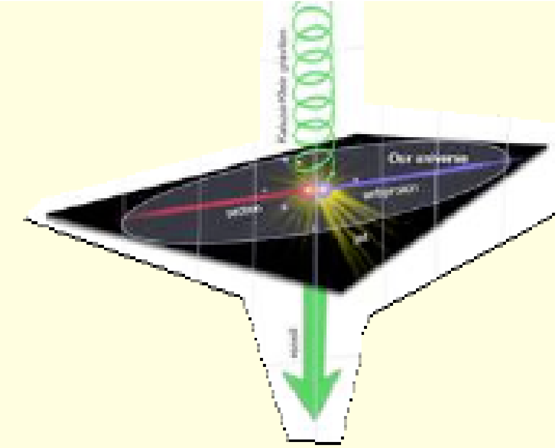



Drawing by K. Loureiro

# ADD signatures

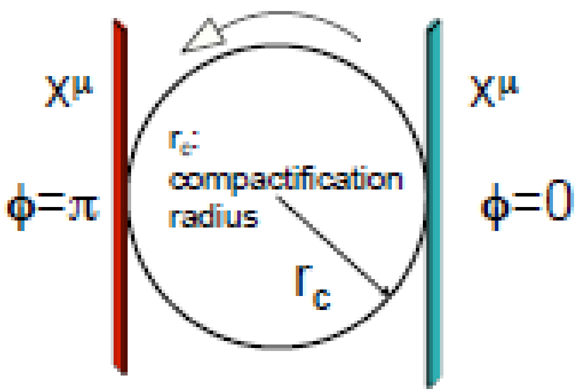
- Edges of extra dimensions identified
  - ➡ Boundary conditions
  - ➡ Momentum along extra dimension is quantized
  - Looks like mass to us
  - Very small separations → looks like continuum
  - Called Kaluza-Klein tower
- Coupling to single graviton very weak, but there are *lots* of them!
  - Large phase space → observable cross-section
    - Impacts all processes (graviton couples to energy-momentum)

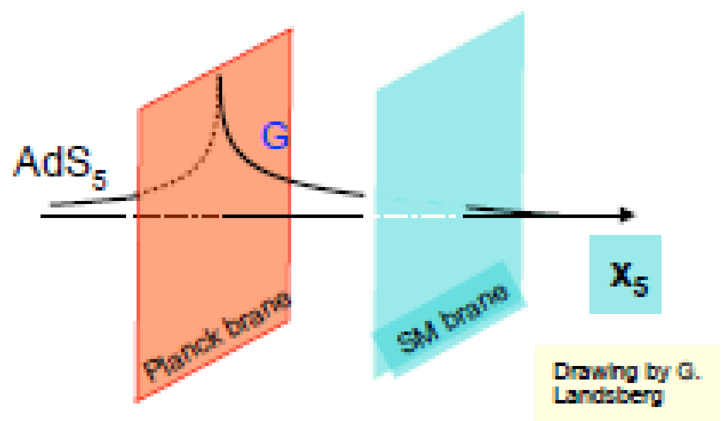
- Consider processes that involve the bulk (i.e. gravitons)
  - Translational invariance is broken
    - ➡ Momentum is not conserved ...
    - ... because graviton disappears in bulk right away
- Look for p p → jet/photon + nothing (i.e. $\not{E}_T$), or deviations in high mass/angular behavior in standard model processes
  - Graviton has spin 2, couples to energy-momentum!



# Warped extra dimensions

- "Simple" Randall-Sundrum model:
  - SM confined to a brane, and gravity propagating in an extra dimension
  - As opposed to the original ADD scenario, the metric in the extra dimension is "warped" by a factor $\exp(-2kr_c\phi)$
  - (Requires 2 branes)



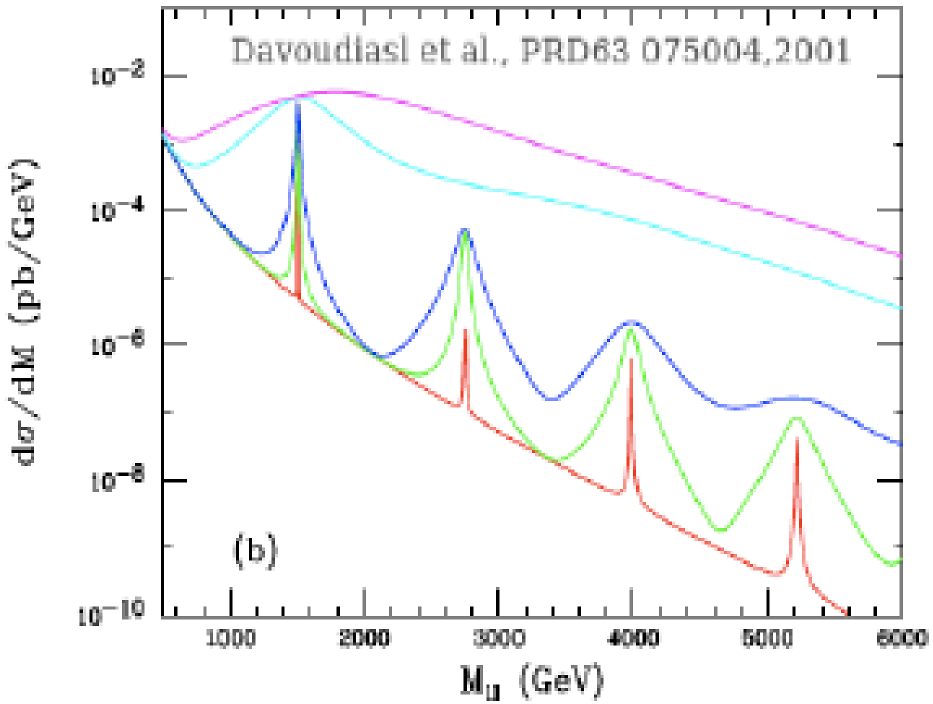



# Graviton excitations

- In RS, get a few massive graviton excitations
  - Widths depend on warp factor k
  - Mass separation = zeros of Bessel function

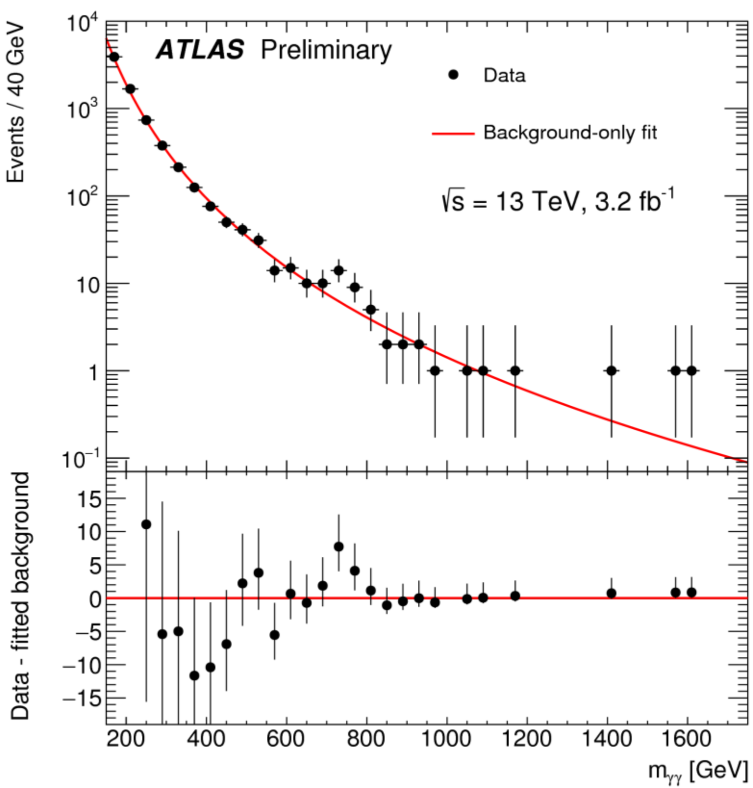
➡ Smoking gun!

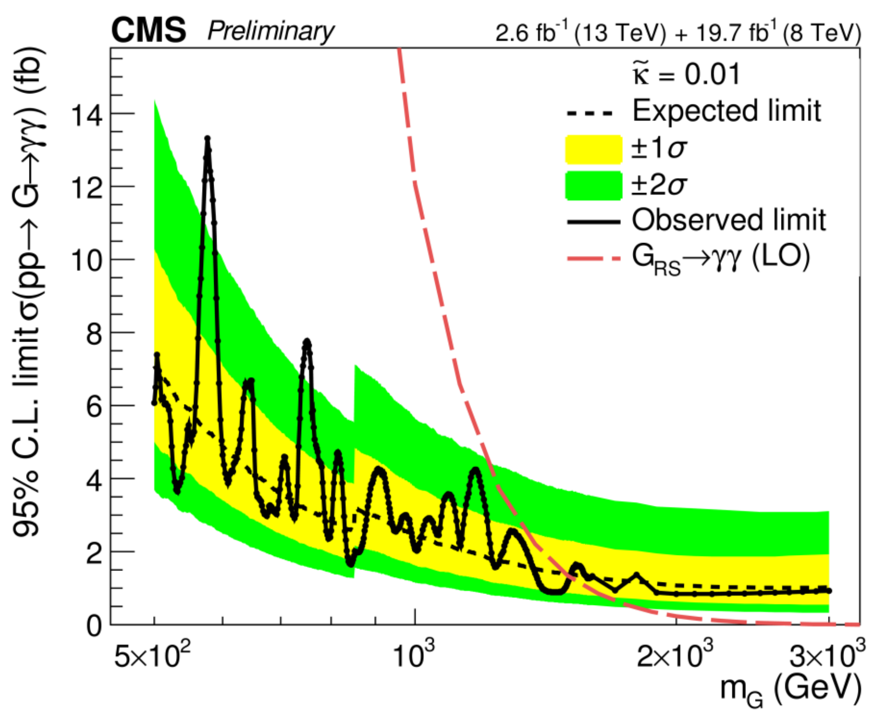
(BRs also different than Z':
e.g. γγ allowed)



# Example

The infamous $\gamma\gamma$ bump is an example of a search for RS gravitons:

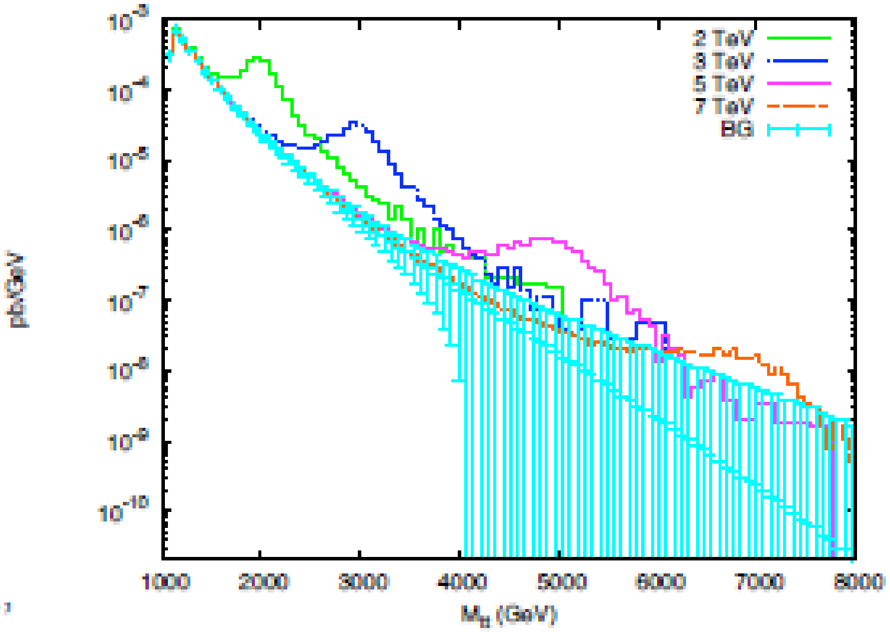


# Gauge boson excitations

- Excitations of the gauge bosons are very promising channels for discovery
  - Couplings to light fermions are small
    - Small production cross-sections
  - Large coupling to top, $W_L$, $Z_L$
    - Look for $t\bar{t}$, WW, ZZ resonances (that can be wide)

B. Lillie et al., JHEP 0709:074,2007

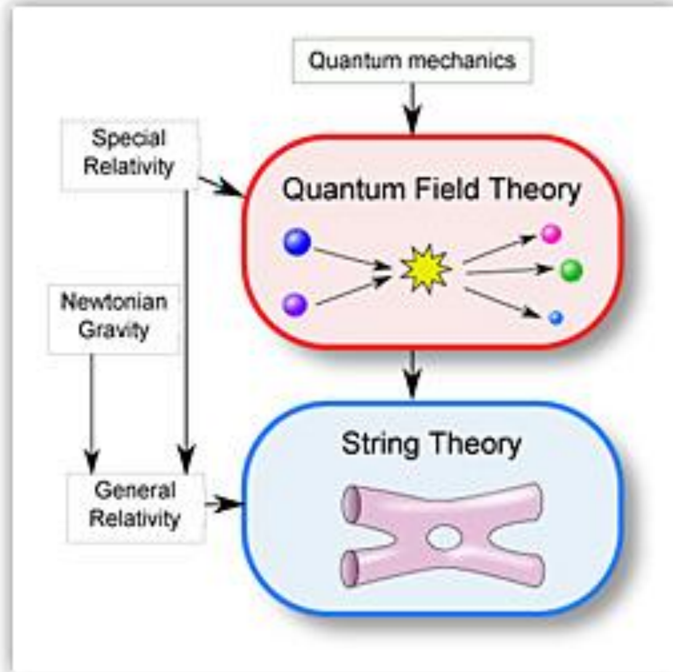


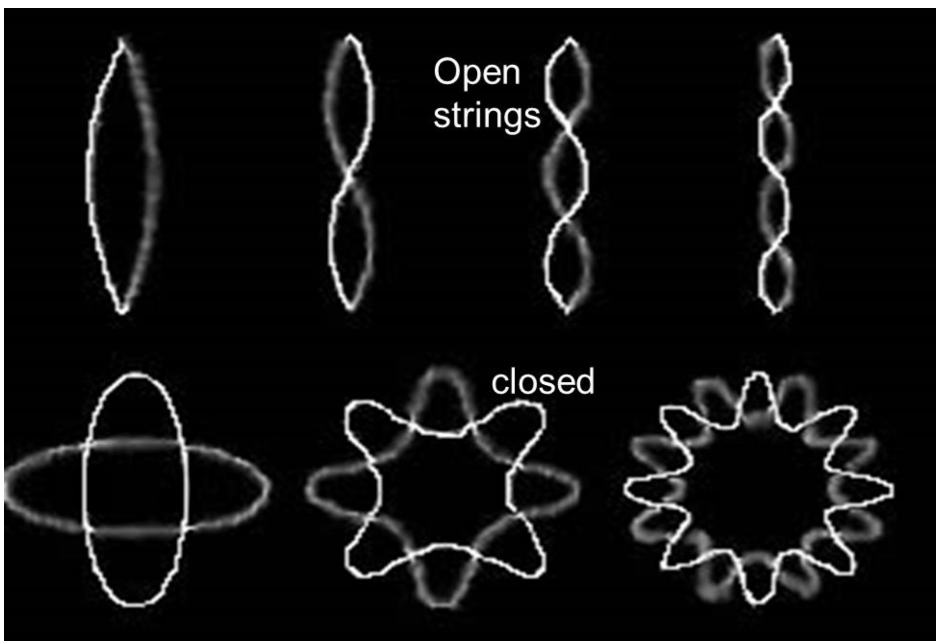
# (super)Strings

Avoid infinities from point-like particles

Different vibration modes = different particles

One fundamental parameter: *string size*




Great idea but we have not yet understood how to test it at current ”low” energies

Extra dimensions a must
Supersymmetry a plus